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An exergy analysis for cement industries: An overview

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ABSTRACT

Cement production has been one of the most energy intensive industries in the world with energy typically accounting about 30–40% of the production costs. Reduction of the production cost is very much important. Therefore, many studies on the efficient use of energy were carried out in the past. Moreover, these studies, which are based on exergy analysis, focus on industrial applications only. This paper reviewed exergy analysis, exergy balance, and exergetic efficiencies for cement industry. It is found that the exergy efficiency for cement production units ranges from 18% to 49% as well as the exergy losses due to the irreversibility from kiln are higher than other units in cement production plant.

Contents

1. Introduction

The cement industry is one of the most energy-intensive industries with energy typically accounting about 30–40% of the costs of production [1]. According to several studies and the results

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Nomenclature

$A(1)$	cooling air of clinker cooler, m^3
$A(2)$	exhaust air from clinker cooler, m^3
$A(3)$	secondary air of rotary kiln, m^3
$A(4)$	tertiary air, m^3
$A(5)$	combustion air of rotary kiln, m^3
$A(6)$	combustion air of calciner, m^3
$A(7)$	primary air, m^3
Cp	specific heat at constant pressure, J/(kg K)
Ex	exergy
ex	specific exergy
ex_{ep}	exergy of electric power, kJ/kg
ex_f	exergy of fuel, kJ/kg
ex_{np}	exergy of non-power-generating raw material fed to the kiln, kJ/kg
ex_p	useful exergy of the product, kJ/mol
$ExSG(1)$	exergy of combustion species in rotary kiln, kJ/(kg clinker)
$ExSG(cal)$	exergy of combustion species in calciner, kJ/(kg clinker)
FA	false air
FR	farine
G	mass flow rate of dry gas, kg/s
ΔG_i	Gibbs energy of the ith reference substance at a given ambient temperature, kJ/mol
H	enthalpy, J/mol
h	specific enthalpy, J/mol
I	exergy destruction, W
L	length of tower
M	molecular weight, kg/mol
m	mass
m_{ik}	stoichiometric coefficient of the kth element in the ith substance
N	number of chemical elements
NHV	net heating value, kJ/kg
P	pressure, MPa
Q	heat transfer, kJ
R	gas constant, J/(mol K)
RB	rotary burner
S	entropy
$SD(n)$	inlet stack dust
$SD(n+1)$	outlet stack dust
$SG(n)$	inlet stack gas
$SG(n+1)$	outlet stack gas
s	specific entropy
T	temperature, K
W	work, kJ
Wei	weight percent of water in fuel, %
X	mole fraction
x_i	concentration of the ith substance in the atmosphere
y	absolute humidity, kg/kg
Z	heat of evaporation, kJ
z	height

Greek symbols

θ	relative humidity
η	exergy efficiency, %
μ	viscosity

Subscripts

a	air
ck	clinker
$dest$	destruction
ex	output
f	flow
in	input
k	location
l	loss
o	environmental state
oo	chemical potential at chemical equilibrium with environment
ref	reference state
sur	surrounding
sys	system
tot	total
t	time
v	vapor
w	water

Superscripts

*	environmental state

obtained the production for each ton of cement consumes energy from 4 to 5 GJ/ton. This energy share of the cement industry in the industrial field is found to be ranging between 12% and 15%. For considering all kinds of industries, this share changes between 2% and 6% in terms of total consumption of energy [2].

Known energy sources have been exhausted rapidly at the moment time in addition rising the energy costs [3]. Several studies are currently going on controlling the mechanisms responsible for the energy degradation to minimize the system losses and to reduce the costs [4]. As energy analysis fails to indicate both the energy transformation and the location of energy degradation, in recent years, emerged a growing interest in the principle of special ability to measure different types of energy to work and popularly known as exergy [5].

Extensive application of exergy analysis can lead to reduce the natural resources use and, thus, to decrease the environmental pollution. The main purpose of exergy analysis is to detect and assess quantitatively the thermodynamic imperfections' causes of thermal and chemical processes. The exergy method of thermodynamic analysis is based upon both the first and the second laws of thermodynamics together, while the energy analysis is based upon the first law only. It is a feature of the exergy concept to allow quantitative assessment of energy degradation [6].

Recently, there is a growing interest in the use of both the energy analysis and the exergy analysis assessments for energy utilization to save energy and thereby achieve financial savings. Dincer et al. [7] applied the energy and exergy analyses in the industrial sector of Saudi Arabia, Utlu and Hepbasli [3] studied these analyses in the Turkish industrial sector, Al-Gandoor et al. [8] presented the energy and exergy utilization of the USA manufacturing sector. Energy and exergy analyses were applied in many sectors in Malaysia, namely, process heating in the industrial sector [9], transportation sector [10], utility and commercial sector [11] and residential sector [12]. As mentioned above the consumption of energy and production costs keep increasing, thus the energy cost's ratio, which is an important parameter in the total production cost, has reached 50%. Energy cost of a cement sector has the highest proportion with 55%, when compared with other industrial sectors [13]. Saxena et al. [14], Worell et al. [15], Khurana et al. [16], Engin and Ari [17] studied to improve the energy efficiency for the cement sector. In this work, we reviewed the exergy analysis, exergy balance, and exergetic efficiency for the units which relate to the production processes in the cement industries.

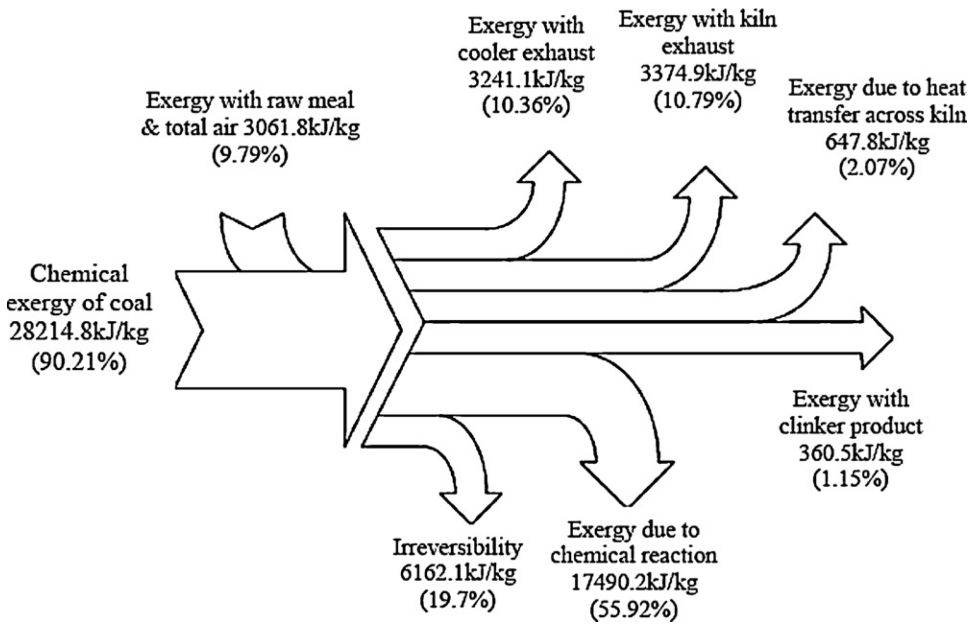

Fig. 1. Diagram of exergy flow for the kiln system [20].

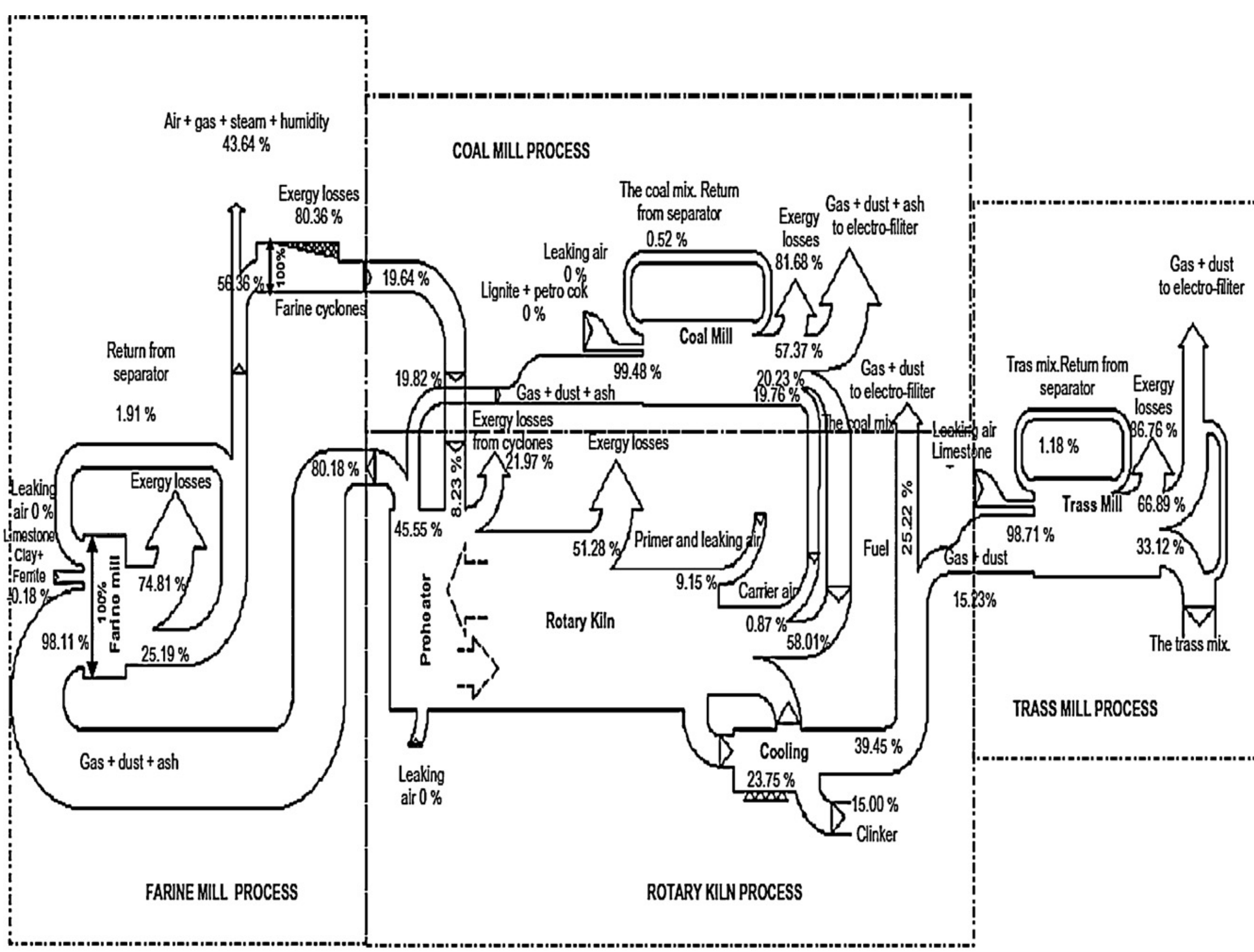

Fig. 2. Exergy diagram of the cement production line [21].

2. Exergy

Exergy is the maximum work potential of a system, stream of matter, or a heat interaction as the datum state in relation to the reference environment [18]. Furthermore, exergy could be defined as a measure of the minimum work required to produce goods, evaluation of energy conversion, and for production systems utilization [19]. Also exergy can be known as available energy, availability, exergy, technical work capacity, usable energy and work potential [18].

2.1. Exergy related to the steady matter stream (flow exergy)

A matter stream may be classified as including the thermo-mechanical exergy and chemical exergy due to the recent definitions. It has three types: physical exergy, kinetic exergy and potential exergy. Most of the time, potential and kinetic exergy variations can be represented the negligible value, and they are not considered into the analysis of exergy. For the material stream, the total content of exergy is obtained by summing up these exergies as mentioned above. Thus, the specific exergy on a mole basis of a moist air ideal mixture can be obtained by the following expression [4]:

$$ex_t = x_a[h_a - h_a^* - T_0(s_a - s_a^*) + \mu_a - \mu_{a,00}] + x_v[h_v - h_v^* - T_0(s_v - s_v^*) + \mu_v - \mu_{v,00}] \quad (1)$$

The dead state was represented by the subscript 00 in the above equation. After the substitution and some simplifications for the related expressions in the previous equation, the total air exergy is given by the following equation [4]:

$$Ex_a = G_y \left\{ (Cp_a + yCp_v)\left(T_a - T_0 - T_0 \ln\frac{T_a}{T_0}\right) + R_a T_0 \times \left(1 + \frac{M_a}{M_v}y\right) \ln\frac{1+(M_a/M_v)y_{00}}{1+(M_a/M_v)y} + \frac{M_A}{M_v} y \ln\frac{y}{y_{00}} \right\} \quad (2)$$

where the first term in brackets in the above equation is the air exergy via heat transfer of convection ($Ex_{a,conv}$), while the second term is the air exergy via heat transfer of evaporation ($Ex_{a,evap}$).

The stream exergy content for the liquid may be obtained as follows:

$$Ex_w = L_w[(h_w - h_o) - T_0(s_w - s_o) - R_v T_0 \ln\theta_0] \quad (3)$$

If assume the law of ideal gas, the above equation may write as follows to give:

$$Ex_w = L_w \left[Cp_w(T_w - T_0) - T_0 Cp_w \ln\frac{T_w}{T_0} - T_0 R_v \ln\frac{P_0}{P_w} - R_v T_0 \ln\theta_0 \right] \quad (4)$$

The diagram of exergy flow in kJ/kg, in addition to the exergy flow breakdown in % for the kiln system are shown in Fig. 1.

Analysis of the waste energy potential shows that an intensive amount of heat flows from a rotary kiln surface to the environment. Due to the exergy analysis, as shown in Fig. 2 the flow diagram demonstrates the exergy flow of whole processes on the cement production line [21].

The improvement and the optimization of the energy process may be allowed by the identification and quantification of the exergy loss's sources [22]. It is considered in the cooler than the flows of heat dissipation losses are rejected to the ambient air with (T_0). For the open system, exergy balance in a steady state for clinker cooling as shown in Fig. 3 can be expressed as:

$$Ex_{dest} = (m_{ck}ex_{ck,in} + m_{a1}ex_{a1} + m_{a2}ex_{a2}) - (m_{ck}ex_{ck,ex} + m_{as}ex_{as} + m_{aexh}ex_{aexh}) + W \quad (5)$$

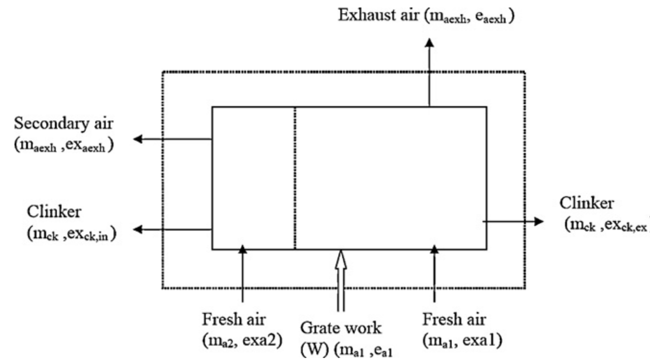

Fig. 3. Mass and exergy flow diagram of clinker cooler [23].

Eq. (5) includes three terms: The specific exergy related to the clinker and the air, work rate flow and the exergy destroyed of flow due to the irreversibility.

2.2. Specific exergy

The specific exergy of the clinker and the humid air at (T, P) due to the function of the physical exergy [24] are respectively expressed by the following equations:

$$ex_{ck} = (h_{ck} - h_o) - T_0(s_{ck} - s_{s_o}) \quad (6)$$

$$ex_a = (h_a - h_o) - T_0(s_a - s_o) \quad (7)$$

where T_0 is the temperature at ambient = 298 K, P_0 is the pressure of atmosphere = 101.325 kPa. The kinetic exergy and potential exergy are neglected.

As perfect gases and pure substances ideal mixtures, the clinker and the humid air are considered, the specific exergy of clinker and humid air are calculated by the following equations:

$$ex_{ck} = \sum_{i=1}^{n} X_i \left(\int_{T_0}^{T} CP_i(T)dT - T_0 \int_{T_0}^{T} CP_i(T)d\ln(T) \right) \quad (8)$$

$$ex_a = \sum_{i=1}^{n} X_i \left(\int_{T_0}^{T} CP_i(T)dT - T_0 \left[\int_{T_0}^{T} CP_i(T)dT \ln(T) - \frac{R}{M_i} \ln\frac{P}{P_0} \right] \right) \quad (9)$$

2.3. Physical exergy

A maximum amount of shaft work, which is obtained from a substance, when the state of substance changed from initial state to the environmental state by means of physical processes, involving interaction only with the environment. Physical exergy is also known as thermo-mechanical exergy [18].

2.4. Chemical exergy

If the system consists of N chemical elements, then there will be N reference substances and for each of them can be written by the following expression:

$$\Delta G_i + \sum_{k=1}^{N} m_{ik} e_k = (0 \vee -RT_0 \ln x_i), \quad i = 1, \ldots, N \quad (10)$$

On the basis of this equation, there is a set of N equations, which represent the values of elements of chemical exergy. It is important to

Table 1
Types of exergy flow in the kiln in the cement industry [25].

Flow	Thermo-mechanical exergy	Chemical exergy		Heat flow exergy	Radiation exergy
		Reaction exergy	Concentration exergy		
Raw material	–	–	–	–	–
Primary air and air fed to cooler	–	–	–	–	–
Secondary air and excess air	+	–	–	–	–
Fuel	+	+	–	–	–
Clinker	+	+	–	–	–
Waste gas	+	+	+	–	–
Heat loss through kiln body	–	–	–	–	–

choose the reference substances, so that the other elements' chemical exergies are more than zero. On the other hand, if the certain substance has chemical exergy less than zero. Therefore, it should be taken as a reference substance, and it is replaced instead of one of the previously chosen reference substances. But if there are several substances with chemical exergy have negative value. A reference substance is taken to be the compound with the minimal exergy [25]. Exergy flow types in the kiln system are shown in Table 1.

Brodyanskii et al. [26] established the procedure to the chemical exergy using the thermodynamic data which obtained from [27,28]. Karimi and Abedi [1], Koroneos et al. [29] calculated the chemical exergy which is considered into accounts. Trubaev [25] proposed a method to chemical exergy calculation with allowance for the chemical composition and the temperature of ambient. He performed the analysis of exergy of cement clinker burning. In the clinker production, the initial substances and the end products with the environment are in equilibrium. Consequently, in the exergy calculation, the chemical exergy only characterized the materials, and the thermo-mechanical exergy ignored [30].

The chemical exergy of the stack dust flow at the rotary kiln exit and cyclones stages exit as well as the raw material chemical exergy at the entrance of cyclone stages can be expressed as follows [31]:

$$\begin{aligned} Ex_{ch} = {} & ex_{ch,\mathrm{CaCO_3}} \cdot m_{\mathrm{CaCO_3}} + ex_{ch,\mathrm{MgCO_3}} \cdot m_{\mathrm{MgCO_3}} \\ & + ex_{ch,\mathrm{CaO\cdot SiO_2}} \cdot m_{\mathrm{CaO\cdot SiO_2}} + ex_{ch,\mathrm{Al_2O_3\cdot SiO_2}} \cdot m_{\mathrm{Al_2O_3\cdot SiO_2}} \\ & + ex_{ch,\mathrm{Fe_2O_3\cdot SiO_2}} \cdot m_{\mathrm{Fe_2O_3\cdot SiO_2}} + ex_{ch,\mathrm{SiO_2}} \cdot m_{\mathrm{SiO_2}} \end{aligned} \tag{11}$$

Clinker chemical exergy can be obtained by the following expression:

$$\begin{aligned} Ex_{ck_{ch}} = {} & ex_{ch,\mathrm{C_2S}} \cdot m_{\mathrm{C_2S}} + ex_{ch,\mathrm{C_3S}} \cdot m_{\mathrm{C_3S}} \\ & + ex_{ch,\mathrm{C_3A}} \cdot m_{\mathrm{C_3A}} + ex_{ch,\mathrm{C_4AF}} \cdot m_{\mathrm{C_4AF}} + ex_{ch,\mathrm{MgO}} \cdot m_{\mathrm{MgO}} \\ & + ex_{ch,\mathrm{CaSiO_2}} \cdot m_{\mathrm{CaSiO_2}} \end{aligned} \tag{12}$$

2.5. Exergetic contents of fuels

On the thermal performance, extremely useful information can be obtained via heat balance for any system. It shows where and how the consumption of the heat generated by the fuel is occurred [20].

The lowest values of the consumption of specific heat as a result of the increase in clinkering plants number based on the dry process and calciner.

For a foreseeable period, the cement industry remains as an important consumer of fossil fuels. As well as it is sustained by the fact of clinker manufacturing, there are no other heat sources can be taken into consideration, which can be possible in other fields of the domain of the oxide materials. One of the most important ways to solve the issue is that of increasing the fuels' number which can be burnt in the clinkering plant. The fuels range over enlargement, which can be used in manufacturing of clinker, raises the problem of deciding one fuel over another.

The exergy of pet-coke, heavy fuel oil (HFO) and propane represent the entering exergy to the system which are burned in the clinker production process. The propane value is neglected due to its very low contribution to the system [32]. Koroneos et al. [32] calculated the chemical exergy of the fuel entering the system. The results for pet-coke and heavy fuel were presented in Table 2.

Radu et al. [33] applied a series of classification criteria to a set of 18 fuels. As well as they gave a statistical model to improve for obtaining the best solution inside a set of fuel options.

2.6. Exergetic efficiency

There are different ways to formulate exergetic efficiency as expressed by the following equation [24,34–36]:

$$\eta_1 = \frac{\dot{E}x_{ex}}{\dot{E}x_{in}} \tag{13}$$

$$\eta_2 = \frac{\dot{E}x_{ex} - \dot{E}x_{waste}}{\dot{E}x_{in}} \tag{14}$$

$$\eta_3 = \frac{\dot{E}x_{desired,exit}}{\dot{E}x_{used}} \tag{15}$$

or

$$\eta_3 = \frac{\text{Desired exergetic effect}}{\text{Exergy used to drive the process}} = \frac{\text{Product}}{\text{Fuel}} \tag{16}$$

Trubaev and Besedin [30] proposed a generalized form of thermodynamic criteria for the efficiency of clinker production, which takes into account the raw material and clinker types.

The kiln exergy efficiency can be obtained by the following equation [37]:

$$\eta_{\mathrm{kiln}} = \frac{ex_p - ex_{np}}{ex_f + ex_{ep}} \tag{17}$$

The efficiency of the first law for clinker cooler is defined by the following expression:

$$\eta_I \frac{\text{Clinker formation energy}}{\text{Input energy}} = 1 - \frac{\text{Output energy}}{\text{Input energy}} \tag{18}$$

while the efficiency of the second law is defined as follows:

$$\eta_{II} \frac{\text{Clinker formation exergy}}{\text{Input exergy}} = 1 - \frac{\text{Output exergy} + \text{Irreversibilty}}{\text{Input exergy}} \tag{19}$$

Abedi [38] presented a simple model which based on the mass, energy and exergy balance data available to evaluate the efficiencies of the first and second law for the kiln and the cooler. Camdali et al. [39], Karimi and Abedi [1] identified the first and second laws of thermodynamic, while Sogut et al. [40] found the values of exergy efficiency ranged from 44.5% to 18.4% at varying dead-state temperature values, which ranged between −18 °C and 41 °C.

In Fig. 4, energy (Sankey) diagram and Fig. 5 exergy (Grassmann) diagram, included the first and the second law efficiency in addition to the irreversibility. The first and the second law efficiency are 51%,

Table 2
Fuels exergy [29].

Fuel	Specific exergy, kJ/kg	Consumption, kg/(kg clinker)	Exergy input, kJ/(kg clinker)
Pet-coke	3.3×10^4	0.096	3.23×10^3
Heavy fuel oil	4.1×10^4	1.42×10^{-4}	5.8
Total	N/A	N/A	3.23×10^3

Table 3
Energy and exergy efficiencies for selected units in cement plant.

	Energy efficiency, %	Exergy efficiency, %	Reference
Raw mill	84.3	25.2	[3]
	84	25	[40]
Rotary kiln	61	49	[21,41]
Trass mill	74	13	[21,41]
Coal mill	74	18	[21,41]
Farina mill	84	25	[21]
Whole system	51	28	[31]

28% respectively and anergy rate as 72%. This shows that the first and second law efficiencies are a little bit low but the anergy rate is a little bit high. In these rates, the raw material, clinker composition and basically the fuel quality effect are important (Table 3).

As shown in Fig. 6 and Table 4, the resulting breakdown with the percentage of efficiencies supplied by electricity and fossil fuels at various dead-state temperatures in the cement industry.

2.7. Exergy irreversibility

In the manufacturing process, each step includes the irreversibility generation and thus the losses of exergy (frequently the exergy losses misinterpreted as losses of energy). The exergy concept contribution is most valuable in its capability to make an objective physical manifestation in the units of energy, regardless of their economic value [42].

Conventional states of Thermodynamic that the balance of exergy accounts for the exergy degradation. The outgoing exergy will be always lesser than the incoming one:

$$\text{Exergy Input} - \text{Exergy Output} = \text{Irreversibilities} > 0.2$$

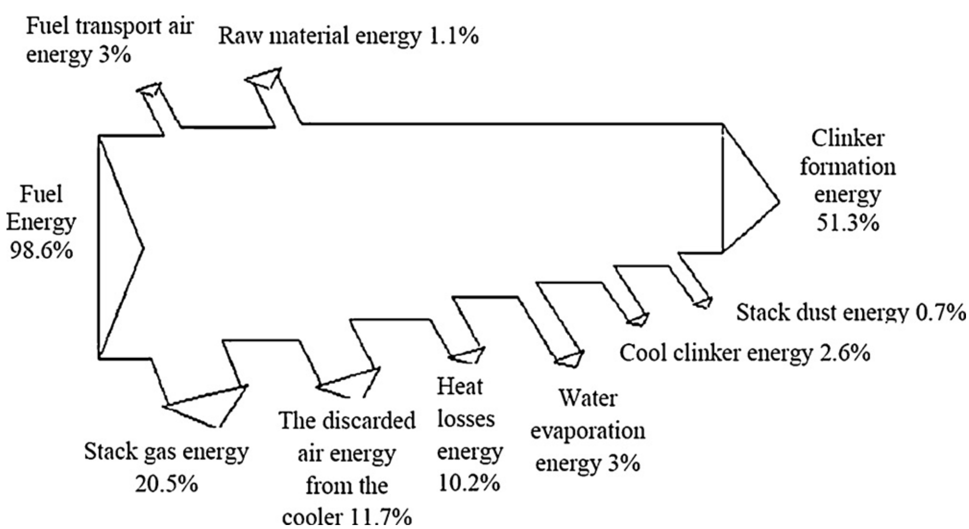

Fig. 4. Sankey (energy) diagram in parallel flow four stages pre-heater cyclone calciner type cement plant [31].

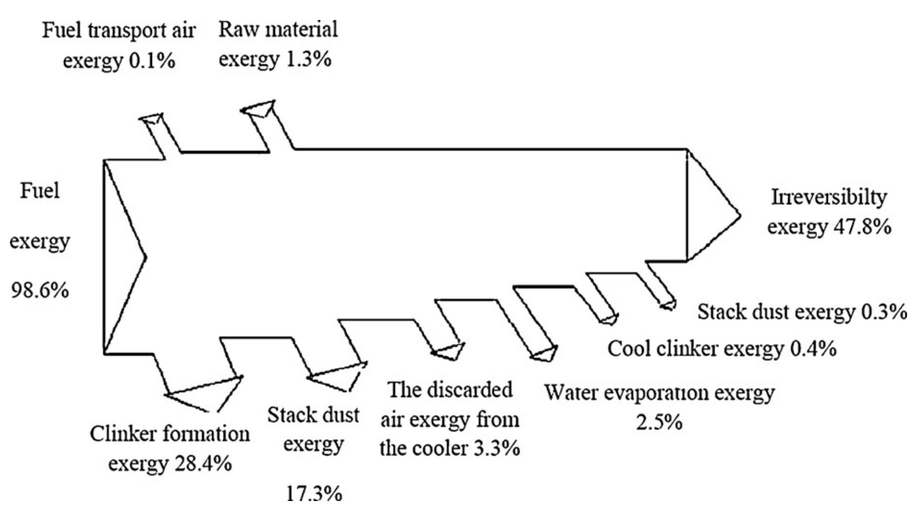

Fig. 5. Grassmann (exergy) diagram for parallel flow four stages pre-heater cyclone calciner type z.

Table 4
Exergy efficiencies at varying dead-state temperature in cement industry [3].

Dead-state temperatures (K)	Electrical heating, ε (%)	Fuel heating, ε (%)	Dead-state temperatures (K)	Electrical heating, ε (%)	Fuel heating, ε (%)
298	8.74	30.97	285	12.62	31.83
297	9.04	31.03	284	12.91	31.91
296	9.34	31.10	283	13.21	31.98
295	9.64	31.17	282	13.51	32.04
294	9.93	31.24	281	13.81	32.11
293	10.23	31.30	280	14.11	32.18
292	10.53	31.37	279	14.40	32.25
291	10.83	31.44	278	14.70	32.31
290	11.13	31.50	277	15.00	32.38
289	11.42	31.57	276	15.30	32.45
288	11.72	31.64	275	15.59	32.52
287	12.02	31.71	274	15.89	32.58
286	12.32	31.77	273	16.19	32.65

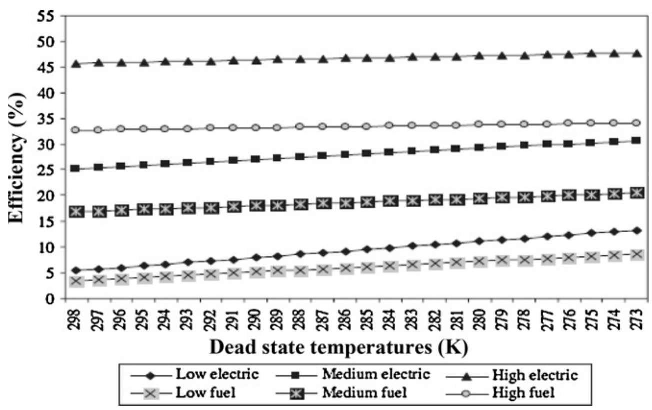

Fig. 6. Exergy efficiencies variation at varying dead-state temperatures in cement industry [3].

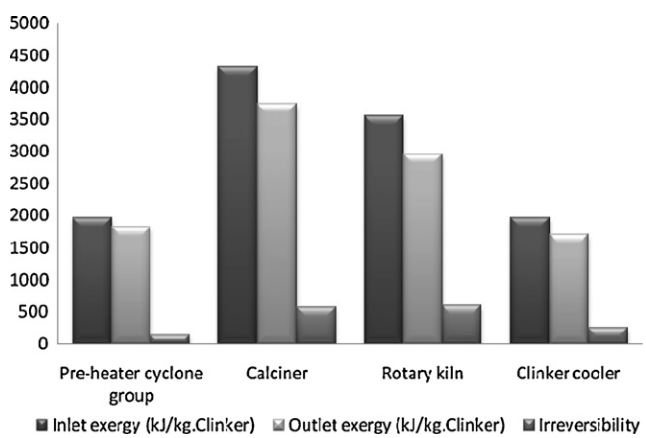

Fig. 7. Irreversibility for each unit within the cement plant [31].

Touil et al. [23] concluded that knowledge of exergetic losses in the grate cooler of the cement industry is known by the exergy analysis. The values of the losses are 50.68 on the level of heat exchange between the air and clinker and 5.08 of the exhaust air. It is considered that losses of the heat dissipation flow of the cooler are rejected to the environment with T_0.

Fig. 7 shows the rotary kiln and calciner maximum exergy destruction because of these units have both combustion and chemical reaction. Rotary kiln and calciner represent the main irreversibility sources in the system with 38.54% and 36.70% respectively, while the clinker cooler and raw feed pre-heating cause 16.13% and 8.64% respectively.

To evaluate the exergy losses in the systems (single flash, Dual-pressure, ORC, Kalina), exergy analysis has been performed as shown in Table 3. It was found that 57.9%, 59.3% and 57.0% of the total input exergy were lost: 28.1%, 29.5%, and 29.8% due to irreversibility in the components, in AQC boiler exhaust 3.7%, 3.7%, and 1.1% to the environment, and 26.1%, 26.1%, 26.1% in the SP boiler exhaust for single flash cycle, Dual-pressure cycle and Kalina cycle respectively. Because of irreversibility, the biggest exergy loss occurs in the turbine expansion process, and the condensation process represents the second process of largest exergy loss in the single fly ash and dual-pressure cycles. On the other hand, the condensation process represents the largest exergy loss and the heat addition process in SP boiler is the second process of the largest exergy loss in the ORC, while the absorption process considers the largest exergy loss and the heat addition process in the kalian cycle.

3. Exergy balance

A general exergy balance, which can be obtained, is an essential way to identify the sources of losses in processes of production [39]. Ogechi [43] represented energy consumption profiles analysis for three companies of cement in Nigeria, as well as he calculated the energy and exergy balance.

3.1. Raw mill exergy balance

The assumptions are steady state and steady-flow process. The following equations represent the exergy balance for raw mill:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{ex} = \sum \dot{E}x_{dest} \quad (20)$$

$$\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_K - \dot{W} + \sum \dot{m}_{in} ex_{in} - \sum \dot{m}_{ex} ex_{ex} = \dot{E}x_{dest} \quad (21)$$

3.2. Cooler exergy balance

Because of the low value of the transiting thermo-mechanical exergy of air and clinker traversing the cooler which constitutes 0.44% of overall exergy input. Consequently, it can be neglected. In spite of the energy efficiency calculated for the cooler is about 85%, the exergy efficiency coefficient of the cooler remains lower than 50% as shown in Fig. 8 [23].

3.3. Kiln exergy balance

For a steady flow system, the exergy balance is given by the following equation:

$$Ex^{in} - Ex^{ex} - E^{Q} - E^{L} = E^{s} \quad (22)$$

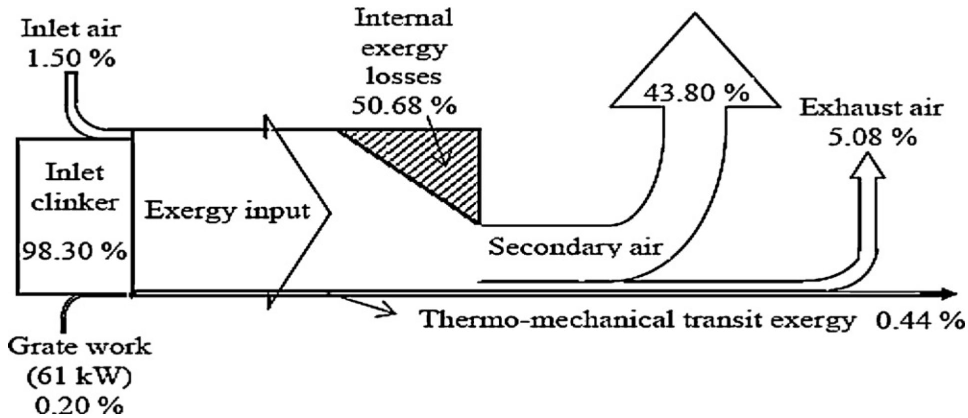

Fig. 8. Cooler exergy balance [23].

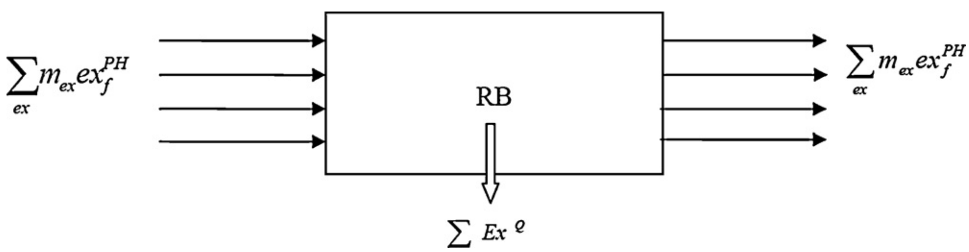

Fig. 9. Going into and leaving exergies of rotary burner [39].

Eq. (22) shows that the irreversibility caused the exergy losses. Eq. (23) can be obtained if Eq. (22) is applied for RB as shown in Fig. 9 as well some assumptions made to obtain these equations such as a steady state and steady flow process assumed this system, as ideal gas assumed the stack gases, potential and kinetic energies variations as well as the substances' chemical exergies are neglected.

$$\sum_{in} m_{in} ex_{in}^{PH} = \sum_{ex} m_{ex} ex_{ex}^{PH} + \sum E^Q + E^L \tag{23}$$

where

$$E^Q = Q_l \times \left(1 - \frac{T_0}{T_{sur}}\right) \tag{24}$$

Camdali and Tunc [44] obtained the general equation of the exergy balance for an open system which is based on the variable temperature and pressure of ambient. Due to this result, they derived the mathematical equations for both the electric arc furnace reversible work given to the system used in steel production and the rotary burner exergy loss used in cement production, as well as they discussed the varying ambient parameter's effects on calculated exergy values in industrial applications.

4. Exergy analysis

Usage of exergy analysis is the main objective to identify and assess the thermodynamic inefficiency's causes. Exergy analysis gives us indications to improve performance of the system. This probable is proportional to the temperature of ambient. So, they determined the fluctuating ambient temperature effects on system exergy and analyzed and discussed the obtained results for two separate industrial applications and one of these applications is rotary burner, which used in cement industry [44].

Compared of different apparatuses or the same apparatus which has different operating conditions can be usually performed by using the exergy analysis [45].

4.1. Exergy analysis with LCA

Ishikawa [46] presented a study to assess the environmental impact. He has shown the importance of using several ways together: Life Cycle Assessment (LCA), Exergy-Mass Analysis (ExMA), and Total Material Requirement (TMR) in addition to the evaluation of the production of cement and ecocement processes. His study results showed exergy of wasted materials of the cement production process is larger than eco-cement production in both types of system boundaries. There is lower exergy emission due to ExMA in an eco-cement process by using LCA and the TMR method shows the same tendency of ExMA.

Bosch [47] developed an exergy-based LCIA method to carry out the assessment of resource consumption in the fuel- and raw-material intensive production of cement.

Pati et al. [48] discussed both LCA and Exergy analysis for industrial processes like cement which is considered one of the most energy and bulk raw material consuming industries. Fig. 9 shows exergy loss and the analysis of exergy (kW) in terms of input, output of a cement plant.

4.2. Cement production exergy analysis

Rasul et al. [20], Karimi and Abedi [1] presented a model to the thermal performance assessment of the cement industry. Rasul et al. [20] provided an integrated vision to improve the plant production. This model which is applied to the Portland cement industry is based on the balance of mass, energy and exergy. On other hand, Karimi and Abedi [1] applied the analysis which comprises an assessment of the energy and exergy input for each stage of the production process.

Koroneos et al. [29] studied the production of cement in Greece using the methodology of analysis of exergy. In the process of cement production, the analysis includes an assessment of energy and exergy inputs at each stage. Although a large quantity of waste heat is being recovered but 50% of exergy is being lost. Sogut and

Oktay [41] applied the analyses of energy and exergy to determine the actual losses of energy and to evaluate the efficiencies of energy and exergy in each process for the cement production plant.

Despite the exergy analysis complements the energy analysis of a cement plant, but it is felt that exergy data integration with life cycle inventorisation will give better insight to every single processing unit of the cement manufacturing process. Fig. 10 shows the contribution of exergy in terms of input, output and losses of various process units in percentagewise.

4.3. Clinker production exergy analysis

A process of clinker production, which is a large amount of the consumption of exergy in the production of PC among the three unit processes. Approximately, it accounts on 94.3% of the total exergy loss in the overall system if it is compared with other processes namely the material preparation and clinker crushing processes [49].

The analysis of the clinker burning process by two first principles of thermodynamics is indicating the importance of energy degradation of the system [50–53].

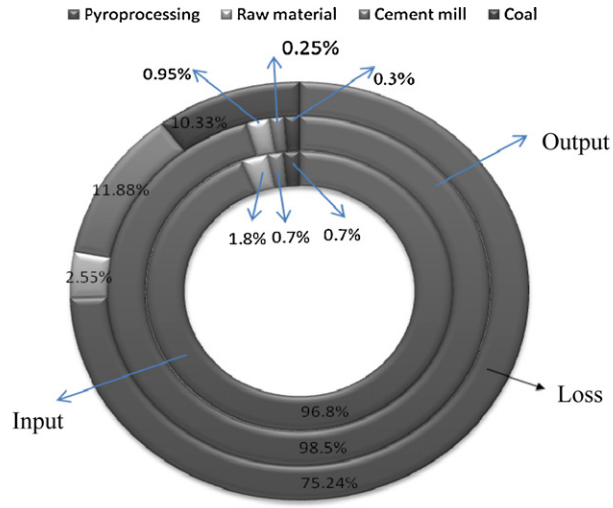

Fig. 10. Exergy analysis (kW) in terms of input, output and exergy loss of a cement plant [48].

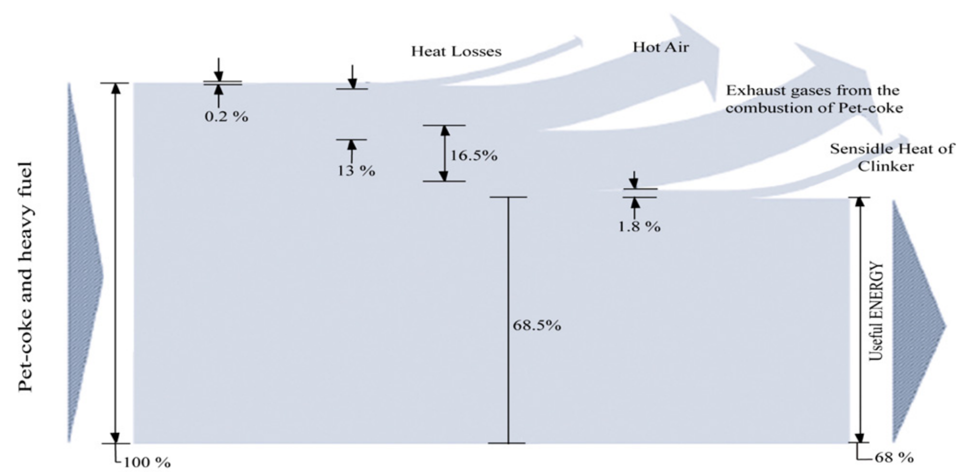

Fig. 11. Energy balance diagram of clinker production [29].

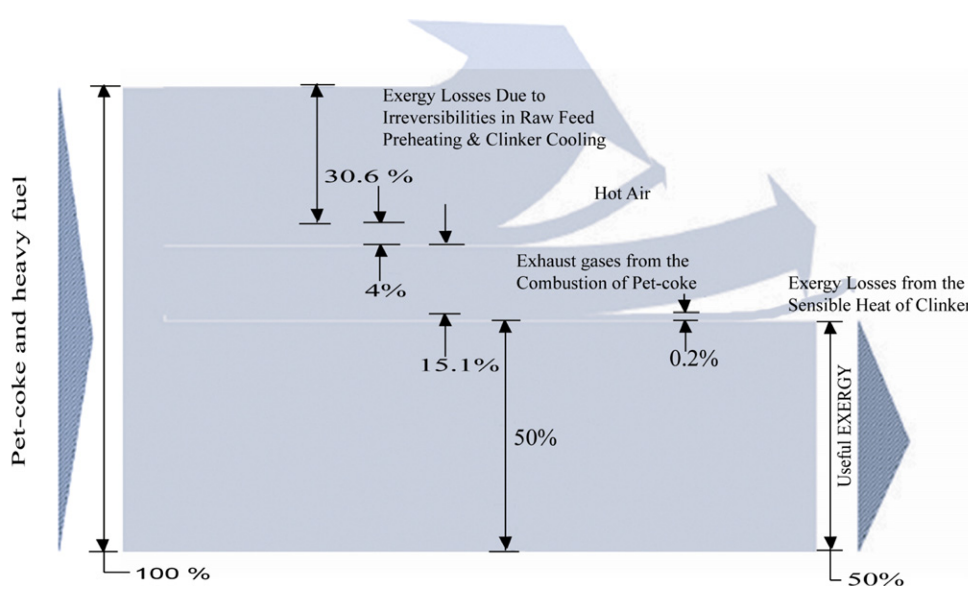

Fig. 12. Exergy balance diagram of clinker production [29].

The energy and exergy balance diagrams (Figs. 11 and 12) give the excellent representation of the exergy and energy balances and of the exergy if it is useful for the process or is destroyed. It is shown that the energy of 68.5% is a useful energy to the system and 50% represents the useful exergy, while the remaining 50% being exergy losses at the various system stages. In the feed pre-heating and the product cooling, the exergy loss of 30.9% which are the biggest losses due to irreversibility.

4.4. Cogeneration system

Cement production ranks among the most energy intensive industrial processes. So as to energy consumption reduction in this process, the waste heat can be recovered via the cogeneration system to produce energy in the electricity form without extra consumption of fuel hence, reduction of electrical energy high cost and CO_2 emissions for the production of cement.

Wang et al. [54] examined the exergy analysis for each cogeneration system in the cement industry (single flash steam cycle, dual-pressure steam cycle, organic Rankine cycle and the Kalina cycle). Also they achieved a parameter optimization for each cogeneration system by means of the genetic algorithm (GA) to reach maximum efficiency of the exergy.

4.5. Raw mill exergy analysis

Utlu et al. [55] performed the analysis of energy and exergy to raw mill in addition to the unit of the raw materials' preparation using the real operating data in a cement plant in Turkey. Sogut et al. [40] presented their study in twofold, the first one is the investigation the varying dead-state temperatures' effects on the analyses of energy and exergy for Raw Mill in a cement plant, While the second one is the examination of energy and exergy sensitivity analyses results, which calculated due to the varying dead-state temperatures.

4.6. Cooler exergy analysis

Niksiar and Rahimi [5] presented a description of the mathematical model to analyze the energy and exergy for a cocurrent gas spray cooling system which based on some operating data for the commercial cement plant in Iran. Mass, energy, and momentum conservation laws were used to calculate the efficiencies of energy and exergy. Touil et al. [23] applied the concept of analysis on the grate cooler, which is one of the parts of the system of clinker burning as well as the rotary kiln and the suspension pre-heater in the cement industry.

Lukawski [56] applied the economic analysis on the clinker cooler in a cement plant and quantified the rates of (exergy flow, exergy destruction, and loss) for all streams in the system.

4.7. Cyclone precalciner

Kolip and Savas [31] developed a mathematical model related to energy and exergy analysis of a parallel flow, four-stage cyclone precalciner type for the cement plant. Kolip and Savas [31] presented the expressions of the energy and exergy balances for the whole system and each unit as shown in the Table 5. Whereas, Kolip [57] presented the energy and exergy analysis of a serial flow, four-stage cyclone precalciner type for the cement industry.

4.8. Exergy analysis of kiln

Camdali et al. [39] examined energy and exergy analyses applications for a dry system rotary burner (RB) with pre-calcinations

Table 5
Expressions for energy and exergy analysis of a parallel flow, four-stage cyclone precalciner [31].

	Energy in	Energy out	Exergy in	Exergy out	Irreversibility
Clinker cooler	$e_{in,cool} = eK(1) + eA(1)$	$e_{out,cool} = eK(2) + eA(2) + eA(3) + eA(4) + QW_{cool}$	$ex_{in,cool} = eK(1) + eA(1)$	$ex_{out,cool} = exK(2) + exA(2) + exA(3) + exA(4)$	$I_{cool} = ex_{in,cool} - ex_{out,cool}$
Rotary kiln	$e_{in,RK} = eF_{RK} + eF(n) + eA(3) + eA(4) + eA(5) + eA(6)$	$e_{out,RK} = eK(1) + eSG(1) + eSD(1) + QR_{RK} + QW_{RK}$	$ex_{in,RK} = exF_{RK} + exF(n) + exA(3) + exA(5) + exA(6)$	$ex_{out,RK} = exK(1) + exSG(1) + exSD(1)$	$I_{RK} = ex_{in,RK} - ex_{out,RK}$
Calciner	$e_{in,CAL} = eF_{CAL} + eF(n-1) + eA(4) + eA(7)$	$e_{out,CAL} = eF(n) + eSG(2) + eSD(2) + QR_2 + QW_{CAL}$	$ex_{in,CAL} = exF_{CAL} + exF(n-1) + exA(4) + exA(7)$	$ex_{out,CAL} = exF(n) + exSG(2) + exSD(2)$	$I_{CAL} = ex_{in,CAL} - ex_{out,CAL}$
Pre-heater cyclone	$e_{in,PRH} = eF(n) + eSG(n) + eSD(n) + eFA(n) + RVE(1) + RCE(2)$	$e_{out,PRH} = eF(n+1) + eSG(n+1) + eSD(n+1) + eFA(n+1) + QR_1 + QW_{PRH}$	$ex_{in,PRH} = exF(n) + exSG(n) exSD(n) + exFA(n)$	$ex_{out,PRH} = exF(n+1) + exSG(n+1) + exSD(n+1) + eFA(n+1)$	$I_{PRH} = ex_{in,PRH} - ex_{out,PRH}$
Whole system	$e_{in,SYS} = eF_{RK} + eF_{CAL} + eF(1) + eA(1)$	$e_{out,SYS} = eK(2) + eSG(n+1) + eSD(n+1) + eA(2) + H_K +$ Total losses	$ex_{in,SYS} = exF_{RK} + exF_{CAL} + exF(1) + exA(1)$	$ex_{out,SYS} = exK(2) + exSG(n+1) + exSD(n+1) + exA(2)$	$I_{SYS} = ex_{in,SYS} - ex_{out,SYS}$ or $I_{SYS} = I_{cool} + I_{RK} + I_{CAL} + I_{PRH}$

Table 6
Exergy sources inputs and outputs to the kiln system [20].

Description	Formula used	Units
Exergy input to the kiln system		
Chemical exergy of coal	$NHV+Z\times Wei$	kJ/kg
Exergy of raw meal input	$X_i\{(H_{T_2}-H_{T_0})-T_0(S_{T_2}-S_{T_0})\}$	kJ/kg
Exergy of primary air input	$X_i\{(H_{T_3}-H_{T_0})-T_0(S_{T_3}-S_{T_0})\}$	kJ/kg
Exergy of cooling air for cooler	$X_i\{(H_{T_4}-H_{T_0})-T_0(S_{T_4}-S_{T_0})\}$	kJ/kg
Exergy output of the kiln system		
Exergy of clinker product	$X_i\{(H_{T_5}-H_{T_0})-T_0(S_{T_5}-S_{T_0})\}$	kJ/kg
Exergy with cooler exhaust	$X_i\{(H_{T_6}-H_{T_0})-T_0(S_{T_6}-S_{T_0})\}$	kJ/kg
Exergy with kiln exhaust	$X_i\{(H_{T_7}-H_{T_0})-T_0(S_{T_7}-S_{T_0})\}$	kJ/kg
Exergy of heat transfer across kiln surface	$(1-(T_0/T_8))\times Q_{13}$	kJ/kg

in a cement plant in Turkey. Purwanto et al. [58] presented a process analysis which based on exergy analysis and its carbon dioxide emission to the production systems of blast furnace cement (BFC). They first carried out the analysis using exergy balances due to the actual operating data in the cement industry.

The exergy inputs' sources to the kiln system are the coal, raw meals, primary air and cooling air and the total input exergy of the kiln system can be obtained by summation the exergy of (coal, raw meal, primary air and cooling air). On the other hand, the exergy products and outputs of the kiln system are exergy of clinker product, cooler exhaust, kiln exhaust, heat transfer across kiln systems and chemical reactions and by the same way to calculate the total input exergy, the outputs and products total exergy can be calculated. The input and output exergy of the kiln system is defined in Table 6.

5. Conclusion

The following conclusions can be drawn from this review on the exergy analysis, exergy balance, and exergetic efficiency in the cement industry.

- It is found that the implementation of exergy analysis on the production line is a very efficient way for improving the performance of the system and reduction of energy costs.
- In spite of the highest energy efficiency for raw mill and farina mill, the exergy efficiency remains lower than 26%. On the other hand, the trass mill has the lowest exergy efficiency within the cement plant.
- The exergy efficiencies and irreversibility vary from 18 to 49% and 136.22 to 607.89 respectively and the efficiency's values of exergy at varying dead-state temperatures in cement industry are proportional inversely with dead-state temperatures.
- The main irreversibility source in the cement industry is the rotary kiln, whereas the raw feed pre-heating causes the lowest irreversibility within the cement plant.
- In the cogeneration systems, the biggest exergy loss occurs in the turbine expansion process, and the condensation process represents the second process of largest exergy loss in the single fly ash and dual-pressure cycles. On the other hand, the condensation process and represents the largest exergy loss and the heat addition process in SP boiler is the second process of the largest exergy loss in the ORC, while the absorption process considers the largest exergy loss and the heat addition process in the kalian cycle.

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